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24-Dimensional Modulation Formats for 100 Gbit/s IM-DD Transmission Systems Using 850 nm Single-Mode VCSEL

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Abstract *Twenty-four dimensional modulation format with 2 bit/symbol spectrum efficiency is proposed and investigated in an up to 100 Gbit/s VCSEL-based IM-DD transmission system with respect to the channel bandwidth and the power budget.*

Introduction

Multi-dimensional (MD) formats have been proposed and thoroughly studied in the coherent optical transmission systems¹⁻³, in which the formats in up to twenty-four dimensional (24D) space has been reported⁴. In the intensity-modulated direct-detection (IM-DD) systems, MD formats have been reported to enhance the bit-to-error ratio (BER) performance and improve the system flexibility⁵. In⁶, an 8-dimensional format enabled with eight consecutive symbols is proposed. However, the 24D formats with the similar principle for the IM-DD systems have not been investigated yet. In this our work we demonstrate 24D modulation format using super-symbols consisting of 24 regular symbols. It carries 48 bits in each super-symbol, which corresponds to 2 bits/symbol. The new MD member is investigated in an IM-DD system using 850 nm single-mode vertical-cavity surface-emitting laser (VCSEL) and multimode fibre (MMF) spans. Its performance is compared with the conventional PAM-4 and 8-dimensional formats. The proposed modulation format is proved to have additional benefits relative to the 8D formats in different transmission scenarios.

24-dimensional formats, Leech24D_n

The proposed formats, i.e. Leech24D_n, are designed according to the densest lattice in 24D space, i.e. Leech lattice (Λ_{24})⁷. The subscript index n indicates the effective number of bits per symbol. The 24D space has been rigorously proved the space with the highest dimension known so far, which has the densest lattice close to the theoretical limits, followed by the eight-dimensional E_8 ⁸. The Λ_{24} can be seen as the union of two cosets of the Leech half-lattice H_{24} ⁹. Each of the coset of H_{24} can be described with the (24,12) extended Golay code G_{24} , combined with a one-bit parity check. This implies that we can use the G_{24} to construct the Leech lattice and therefore en/decode the Leech24D_n symbols. The format with $n=1$ can be treated as a basic unit of the lattice. For the

formats with $n>2$, the whole Leech24D_n lattice is then constructed by paving the basis cells, which is equivalent to the normal PAM- n

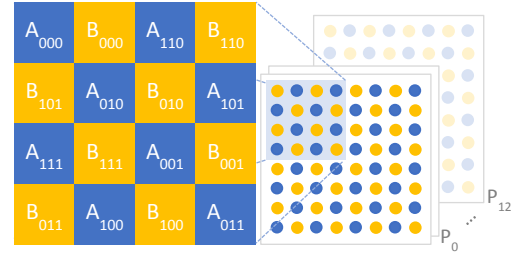


Fig. 1: One 2D facet of the Leech24D_n formats.

modulation on the uncoded bits with the Gray mapping. In Fig. 1, we use one of the 12 two-dimensional projections to illustrate the higher dimensional structure. All 12 points can be selected from either the blue (**A**) or the yellow (**B**) subset. Further division of the subsets relies on the block coding and parity check, which cannot be illustrated directly. The theoretical minimum mutual Euclidean distance (MED) reaches $\sqrt{2}$ times larger than the E_8 based formats, enabling the largest nominal coding gain (6dB) among the other MD formats.

Encoder

To encode the sequence of the conventional symbols into the Leech24D_n ones, we rely on two key components, i.e. a set-partitioning process and a Golay encoding. Fig. 2 shows the basic principles of the encoding scheme. We use Leech24D₂ as an example. The input sequences with 48 bits are encoded into symbol sequences of 24 symbols, i.e. 2 bits per symbol. Among the 48 bits, 24 bits are encoded, with the rest bits modulating the basic unit in a whole like a normal NRZ signal. The coded bits generate 12 position labels (**A**_{ijk} or **B**_{ijk}) for the 2D constellations points. Each symbol is then modulated with the amplitude decided by the 2D label-symbol map shown in the left inset of Fig. 1, together with the uncoded bits. The position label consists of indices i, j, k and the subset index, i.e. **A** or **B**. To determine these indices, we use one bit out of the coded bits to

select the independent subset (either A or B) for all 2D constellation points; 12 bits are encoded by the (24,12) extended Golay encoder and forms the indices i and j for each symbol; and the rest 11 bits together with the first bit form k through a parity encoder. When the position is determined, the symbol sequence is generated according to the point with the label A_{ijk} or B_{ijk} on the bit-to-symbol map Fig.1.

Decoder

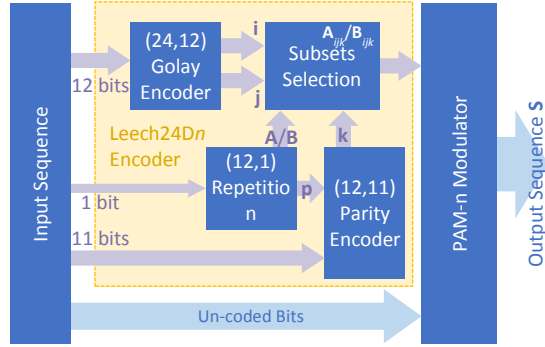


Fig. 2: Flow chart of the Leech24Dn encoder.

For decoding the Leech24D_n symbols, we utilize the half Leech lattice H_{24} decoder and a maximum-likelihood (ML) soft-decision. The process works in parallel on two independent half Leech lattice decoders on **A** and **B**. The decoders output two candidate points. The estimated symbol is decided between the output points of each decoder, with the cost function of the Euclidean distances. Within the decoders, we adapt a ML soft-decoding scheme. The decoder of the Golay enumerates the difference of the MED between the received signal and the target points, which is generated by the Golay generation matrix. The point with the smallest distance difference is selected as the candidate point of one of the H_{24} decoders. To enhance the efficiency, we calculate the MED differences for each cell, namely 16 values for each symbol, and apply a look-up-table to store these MED differences and their position indices on each symbol before the decoding. By doing this, we can avoid the redundant calculation during the decoding. And then the enumeration requires only the summations of the G_{24} code words. The fast decoding of the Golay code and the Leech lattice modulation have been well discussed⁹.

Experimental Setup

In the experiment step shown in Fig. 3, we use an 850 nm single-mode VCSEL coupled with single mode fiber. Its -3dB bandwidth reaches 20 GHz and the maximum output power reaches -1.7 dBm. The laser is modulated by a 65 GSa/s arbitrary waveform generator (AWG) with the modulation amplitude of 750 mV_{pp}. The optical signal is detected by a 22 GHz calibrated photoreceiver module with the co-packaged

transimpedance amplifier (TIA). During the signal generation at the transmitter, streams with 28.8Mbits were randomly generated and mapped into 9.6M symbols, 0.4M super-symbols accordingly. After interleaving, the symbol sequences were resampled to the desired baud rate, shaped into the root raised cosine pulses ($\alpha=0.6$), and pre-distorted to compensate the electrical spectrum roll-off of the AWG. For the digital signal processing (DSP) at the receiver side, the electrical signal was resampled into two times of the baud rate, followed by the synchronization, equalization with a T/2 fractional feedforward equalizer (FFE) and an amplitude correction. After de-interleaving, the output bit streams were obtained by the Leech24D_n de-mapper. The value of each point was given by 10 traces, with 51.25M sampling points of each.

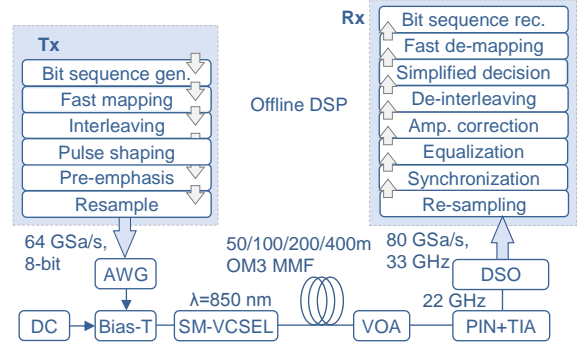


Fig. 3: Scheme of the experimental setup.

Performance

We compare the performance of Leech24D₂ with the conventional PAM-4 and the recently proposed eight-dimensional format, BB8⁶, in different transmission scenarios.

Comparing with other formats: Fig. 4 shows the BER performance of different modulation formats with respect to the received optical power in the case of optical back-to-back and 200m OM3 MMF link. 24D format provides a well recognizable gain at lower BER values over the 8D counterpart, and significantly outperforms standard PAM-4. At 56 Gbit/s in

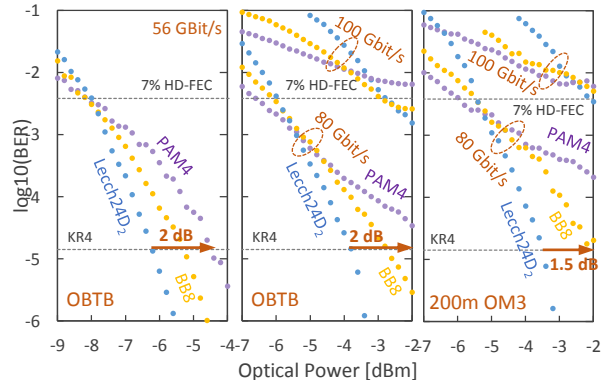


Fig. 4: BER performance vs. received optical power for different transmission scenarios.

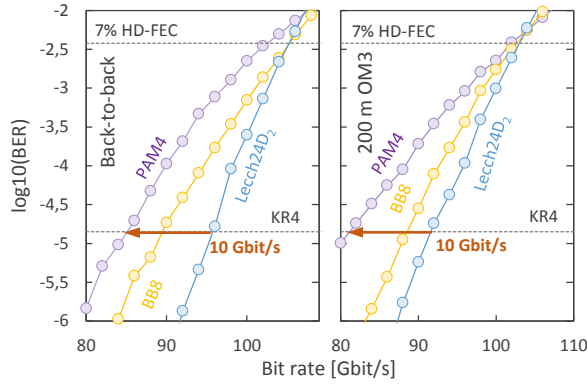


Fig. 5: BER performance vs. channel bit rate.

OBTB regime, Leech24D₂ provides a 2 dB gain relative to PAM-4 in the low-latency KR4 FEC scheme. But at 80 Gbit/s PAM-4 already fails to provide the required BER value of 1.42×10^{-5} within the available power budget of the setup, while 24D modulation guarantees operation under KR4 FEC scheme with a 2 dB power margin. Moreover, 24D modulation shows the possibility of 100G transmission within the hardware limits of our setup, where the PAM-4 exhibits error floor above the standard 7% overhead FEC threshold. The possibility of 100 Gbit/s transmission using the proposed 24D format remains possible over up to 200 m MMF links. In case of 80 Gbit/s transmission over 200m MMF link, 24D format allows data transmission under the BER limit of KR4 FEC with a 1.5 dB power margin, while both PAM-4 and 8D modulation fail.

Bandwidth performance. In Fig. 5, the BER performance of the modulation formats is compared relative to the bit rate, defined by the modulation baud rate. A major capacity enhancement of 10 Gbit/s between Leech24D₂ and the conventional PAM-4 can be observed with respect to the same BER value (KR4 FEC threshold 1.42×10^{-5}).

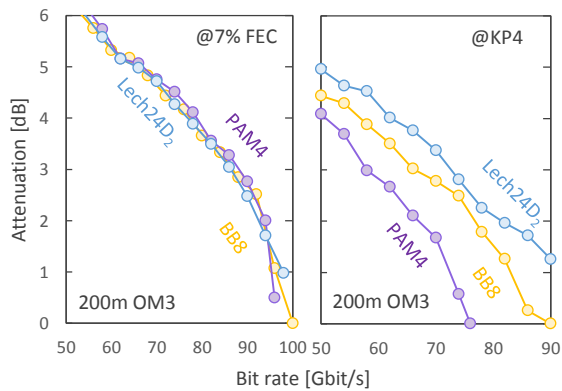


Fig. 6: Power loss tolerance vs. channel bit rate with 200m OM3 MMF link for different FEC schemes.

Power penalty tolerance is estimated in Fig. 6 for different modulation formats and bit rates (defined by corresponding baud rates) in a

200m MMF link. While all considered modulation formats show similar power loss tolerance at the standard 7% overhead FEC threshold, at the KP4 FEC threshold ($BER=2.2 \times 10^{-4}$) 24D format outperforms both the PAM-4 and 8D counterparts, especially for the higher bit rates.

Conclusions

In this work, we propose a new 24D modulation format for IM-DD transmission systems. It shows significant gain at the low BER values compared to the standard PAM-4 modulation and 8-dimensional formats, which implies its potential in the high-speed short-reach communication scenarios, where the use of low overhead FEC schemes with minimized latency is crucial. At the same time, the proposed modulation scheme enables a 100 Gbit/s transmission over 200m OM3 MMF link within the hardware limits.

Acknowledgements

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